An Experiment to Search for $\left\{\begin{array}{c}\nu_\mu \\ \nu_e\end{array}\right\} \to \nu_\tau$ Neutrino Oscillations Using an Enriched $(\nu_e/\bar{\nu}_c)$ Beam

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ABSTRACT

We propose to construct an enriched $\nu_e/\bar{\nu}_e$ beam using K°_L decays and the sign selected bare target beam elements. The $(\nu_e/\bar{\nu}_e)$ beam and the 15' bubble chamber filled with heavy neon will be used to search for ν_τ interactions arising from $\nu_e \to \nu_\tau$ or $\nu_\mu \to \nu_\tau$ neutrino oscillations. Using the present analysis of neutrino oscillations from Barger, et al., we find that $\lesssim 250$ ν_τ interactions could be observed in a 500,000 picture exposure depending on the neutrino mixing parameters. If oscillations are observed, this experiment would also establish the existence of the ν_τ neutrino. The energy of the primary proton beam is 400 GeV, although as an energy saving alternative this experiment could also be operated at a reduced machine energy of 200 GeV with an increased repetition rate.

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Contents

1. Introduction

A recent analysis of existing neutrino oscillation data suggested the possibility that neutrino oscillations may have been observed, but no conclusive evidence exists at present (Appendix A)[1]. The most interesting possibility suggested by this analysis is that $\nu_e \to \nu_\tau$ oscillations may exist with a fairly large mixing angle and δm^2 [1,2]. All previous experiments were insensitive to this kind of oscillation because of low ν_e flux or very large ν_μ flux that produces a large background. We propose to construct an enriched ν_e, $\bar{\nu}_e$ beam with a large ν_e/ν_μ ratio, compared to ordinary beams, in order to carry out a conclusive search for $\nu_e \to \nu_\tau$ oscillations. Figure 1 shows the range of sensitivity required to deserve $\nu_e \to \nu^\tau$ for the two solutions suggested in the analysis of Barger, et al[1,2]. We emphasize that 10 - 30 GeV (ν_e, $\bar{\nu}_e$) beams with long flight paths (> 1 KM) and considerable purity from large ν_μ, $\bar{\nu}_\mu$ flux are necessary to establish the signal of $\nu_e \to \nu_\tau$. Also the present data allow $P(\nu_e \to \nu_\tau)$ between the lower and upper kinks given by beam dump experiments (Fig. 1).

We propose to construct a K°_L beam in the normal neutrino decay channel. Using the Bare Target Sign Selected train load, a modest, inexpensive beam defining system is available[3,4,5]. This system is shown schematically in Figure 2. The most suitable detector to perform this search is the 15' bubble chamber with a neon-hydrogen filling.

The use of the heavy liquid bubble chamber has the following well-known advantages:

1) excellent identification of electrons with <u>both</u> sign and momentum determination.

2) good efficiency in observing and measuring neutrino interactions down to very low energies $\sim$500 MeV/c.

3) excellent visibility of the vertex. It might be possible to see the τ lepton decay vertex depending on τ momentum spectra and lifetime. The addition of the high resolution camera to the stereo triad would considerably enhance this possibility.

4) unbiassed data taking. The detection of events is independent of the kinematic characteristics and/or the event energy.
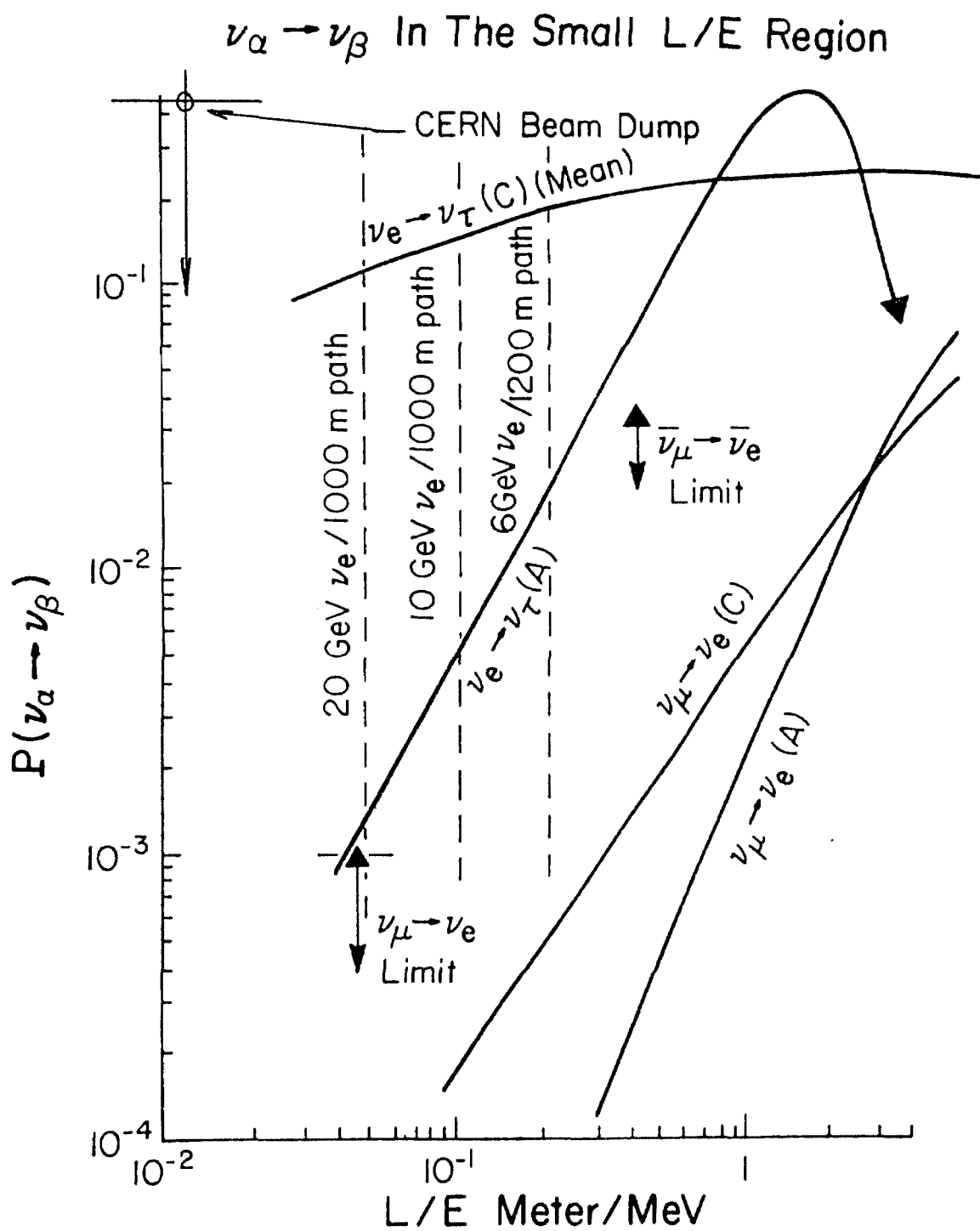
$\nu_\alpha \rightarrow \nu_\beta$ In The Small L/E Region

FIGURE 1

Special $\nu_e, \bar{\nu}_e$ Beam
For Neutrino Oscillation Search

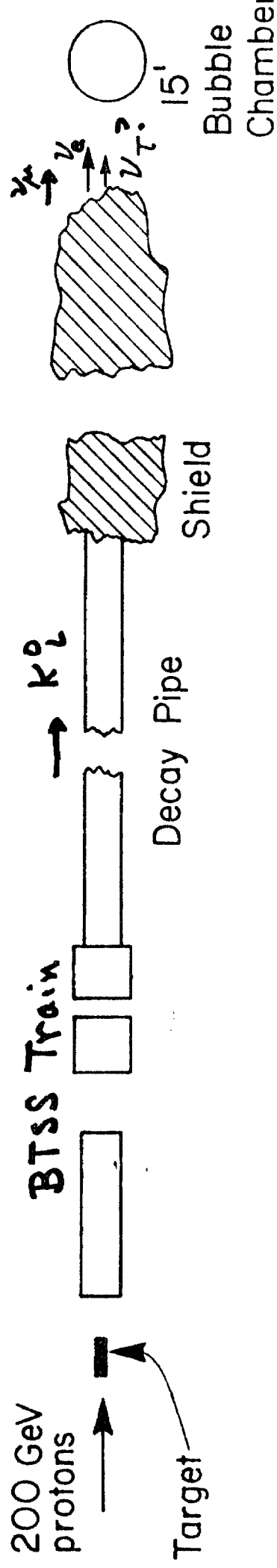FIGURE 2

2. The Search for $\nu_\tau \to \tau$ in the Bubble Chamber

We propose to detect the presence of ν_τ, $\bar{\nu}_\tau$ in the ν_e, ν_μ beam through the signature

$$\nu_\tau + N \to \tau + x$$
$$\hookrightarrow \text{lepton} + \text{missing transverse momentum}$$
$$\to \tau + x$$
$$\hookrightarrow \text{hadrons} + \text{missing transverse momentum}$$

This is schematically shown in Figure 3. Albright et al.[6] and Barger et al.[7] have made extensive calculations for the backgrounds to these signatures from charmed particle production (i.e.)

$$\nu_\mu + N \to \mu + \text{charm} + x$$
$$\phantom{\nu_\mu + N \to \mu + \text{cha}}\hookrightarrow \text{lepton}$$
$$\to \nu_\mu + \text{charm pair} + x$$

In normal neutrino beams the ratio of ν_μ flux to ν_e flux is about 100 to 1. This is about the same ratio as the ratio of lepton pair production by ν_μ through charm. About one order of magnitude smaller there appears to be evidence for events with same sign leptons which may be due to charm pair production. At some level all of these processes may contribute to fake $\nu_\tau \to \tau$ events. Thus it is essential to reduce the larve ν_μ flux in a ν_e beam to reduce these backgrounds. The missing transverse momentum distributions for $\tau^\pm$ production and decay are shown in Figure 4 for leptonic and $\nu_\tau +$ hadronic decays.

We have estimated the expected background contribution for

$$\nu_e + N \to e^\pm + \text{mismeasured hadrons}$$

from existing data and find that less than 3×10^{-3} of ν_e, $\bar{\nu}_e$ interactions should have a "fake" missing $P_\perp$. Thus it appears possible to identify $\tau^\pm$ to this level in the bubble chamber.

The expected cross section and y distribution for production at these low energies are shown in Figure 5 and Figure 6 respectively[8]. The characteristic y distribution might provide additional evidence that $\tau^\pm$ have been observed. The relevant variable in neutrino oscillations is L/E_ν (the ν path length/neutrino energy). Since the path length is fixed, the important measurements are the rates as a function of neutrino energy. No other detector combines the sensitivity and precision at low neutrino energies as does the heavy liquid bubble chamber.
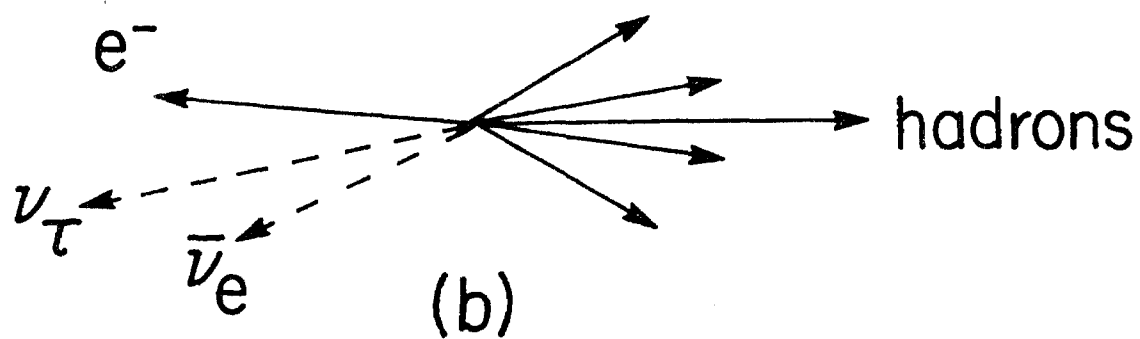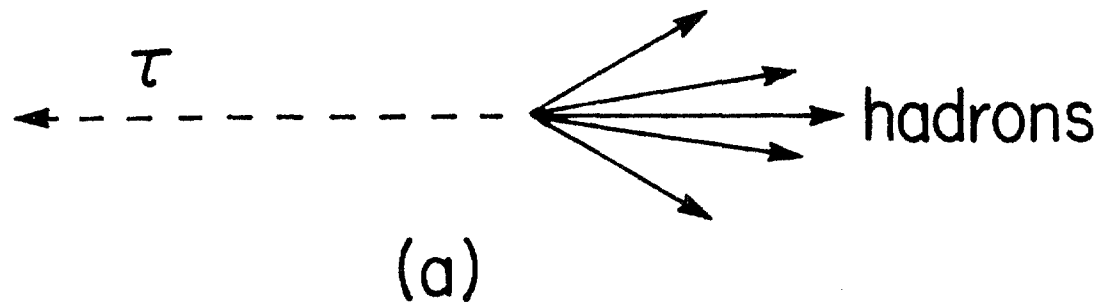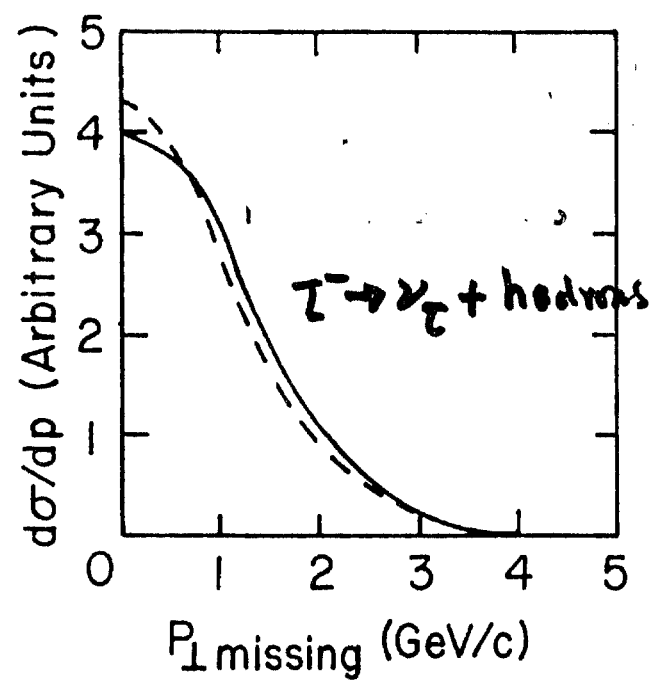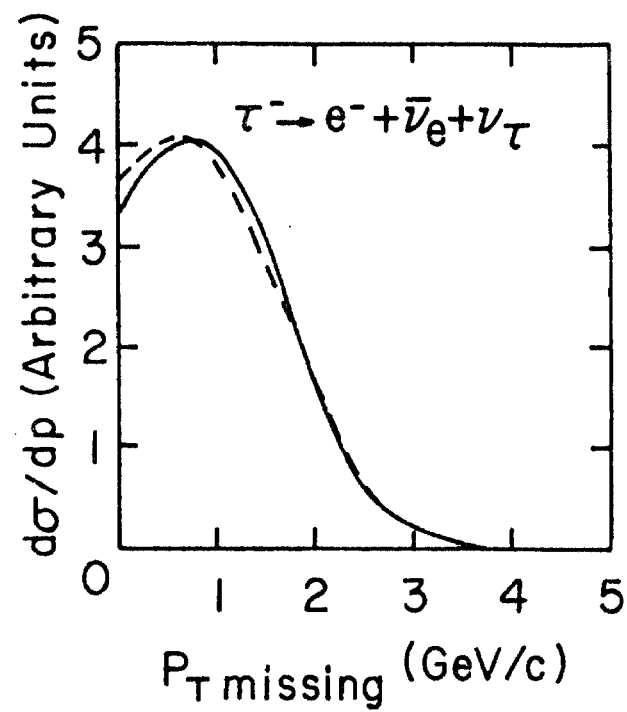
τ Signatures

(a)

(b)

FIGURE 3

$$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$$

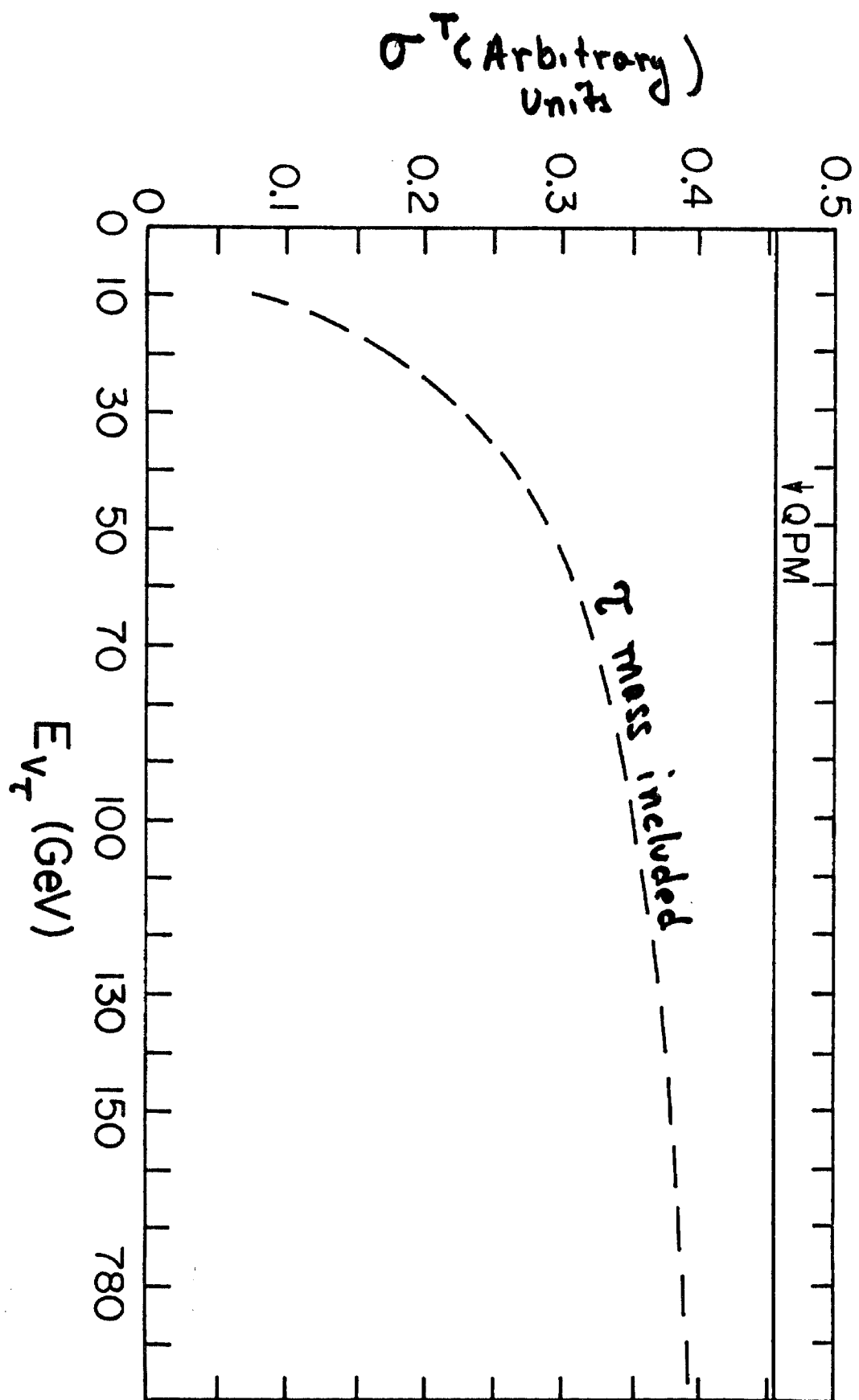$$\tau^- \rightarrow \nu_\tau + \text{hadrons}$$
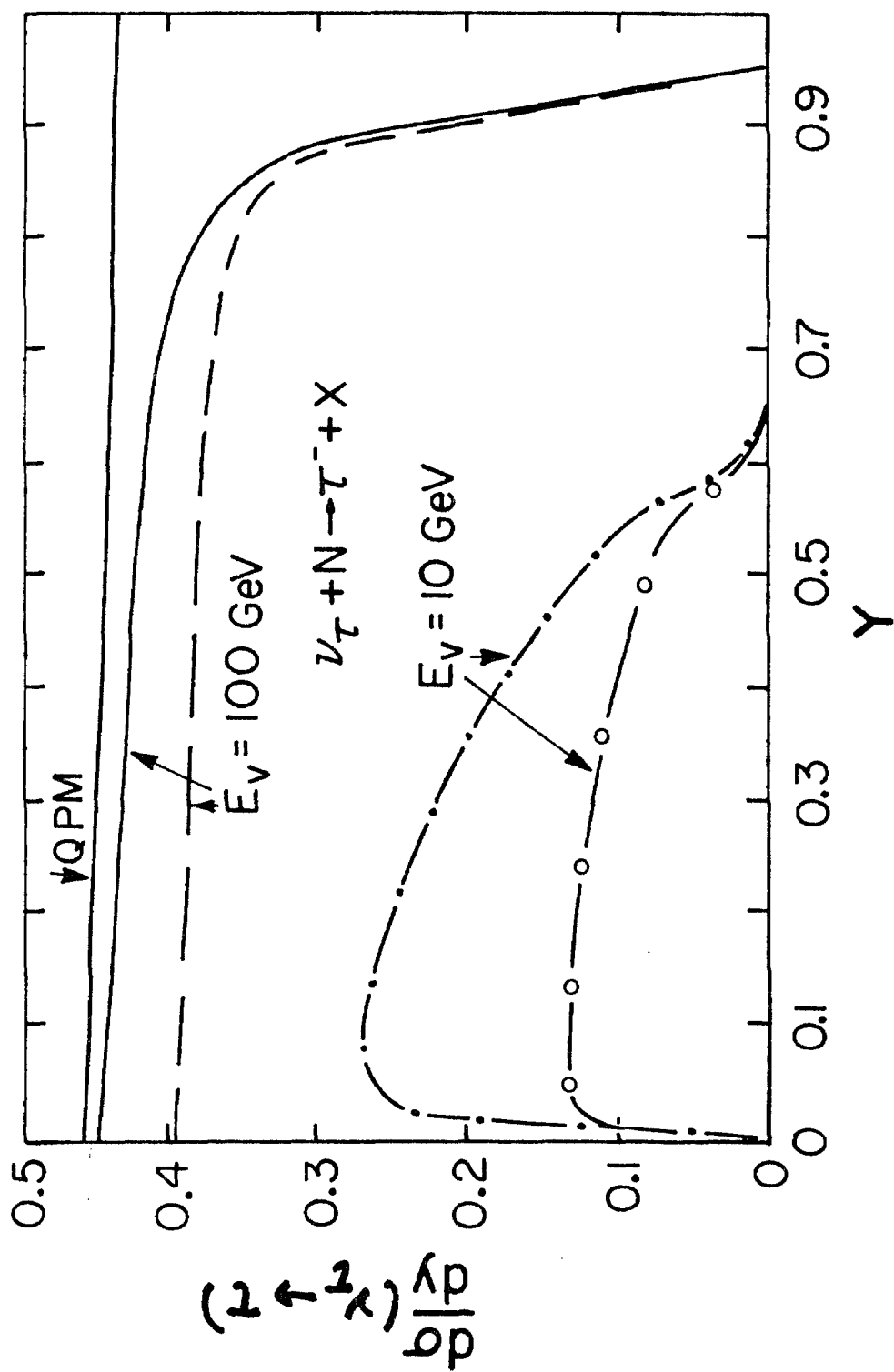
FIGURE 4

FIGURE 5

FIGURE 6

3.   The Enriched $\nu_e/\bar{\nu}_e$ Beam

We propose to use K°_L decay to provide an enriched $\nu_e/\bar{\nu}_e$ beam. Practical beams were discussed some time ago. We follow closely the description by Mori, et al[4,5]:

The Sign Selected Bare Target (SSBT) train used for the HPWF neutrino experiment can easily be modified for an electron neutrino beam. Figure 7 gives a schematic layout of the arrangement[4]. A modification required for the SSBT Beam is to move the dump a few inches to allow the K°_L beam to enter the decay pipe.

Figure 8 shows a calculated electron neutrino or antineutrino flux from the $K^{\circ}_L \rightarrow \pi^- e^+ \nu_e$ (or $\pi^+ e^- \bar{\nu}_e$) decay by a Monte Carlo program. The incident proton energy is 400 GeV. The K°_L production is assumed to be the average K^+ and K^- production. Stefanski-White parameterization was used. Figure 9, 10 shows the spectra for 200 GeV protons. The muon neutrino background from the π^+ and K^+ decays is also shown in Figure 9, 10. This background is relatively independent of the incident proton energy. The muon antineutrino background from the π^- and K^- decays is substantially smaller than the muon neutrino background. The muon neutrino or antineutrino flux from the $K^{\circ}_L \rightarrow \pi^- \mu^+ \nu_\mu$ (or $\pi^+ \mu^- \bar{\nu}_\mu$) is 70% of the electron neutrino or antineutrino flux from the K°_L decay. The muon neutrino or antineutrino backgrounds from pion decays of the $K^{\circ}_S \rightarrow \pi^+ \pi^-$ are estimated to be relatively small in the present arrangement.

In summary, computed electron neutrino fluxes for the present electron neutrino beams are shown in Figures 8, 9, 10 for the incident proton energies of 400 and 200 GeV.

BTSS Beam Set For K_L^0

C1: MAGNET (M1) PROTECTION COLLIMATOR

C2, C3, C4: $\pm$ 2 MRAD XY COLLIMATORS (NO COOLING)

DUMPS: 3 METER LONG ALUMINUM BLOCKS (WATER COOLED)

FIGURE 7

FIGURE 8

$\nu_e, \bar{\nu}_e$ flux with ν_μ background

$E_P = 200\,GeV$

ν_μ Background

$\nu_e, \bar{\nu}_e$

K_S^o

K^+

Neutrinos/GeV/m²/ 10^{13} Interacting Protons

E_ν (GeV)

FIGURE 9

$\nu_e, \bar{\nu}_e$ flux with $\bar{\nu}_\mu$ background

$E_P = 200$ GeV

$\bar{\nu}_\mu$ background

π^-

$\nu_e, \bar{\nu}_e$

K^o_S

K^-

Neutrinos/GeV/m^2/10^{13} Interacting Protons

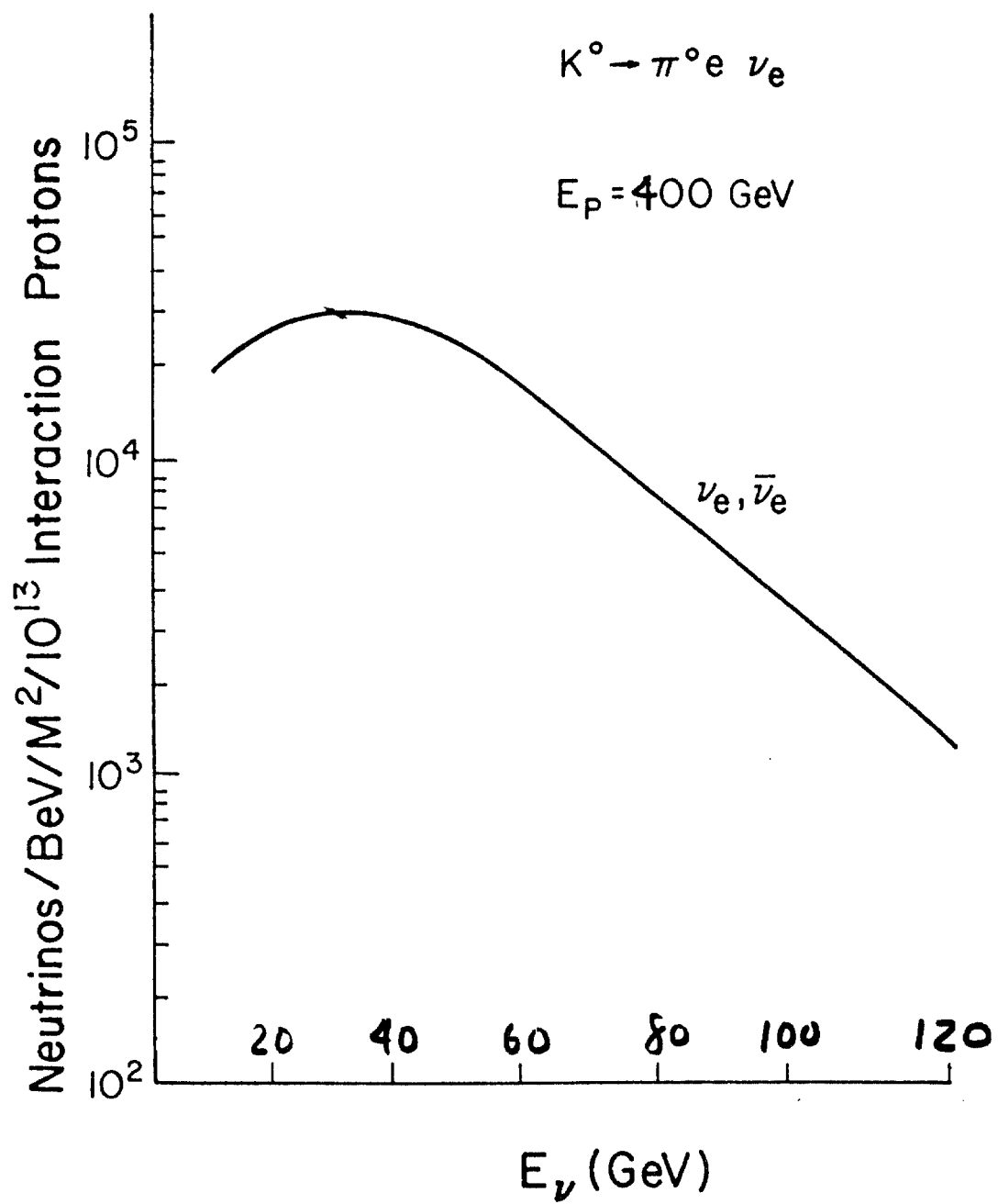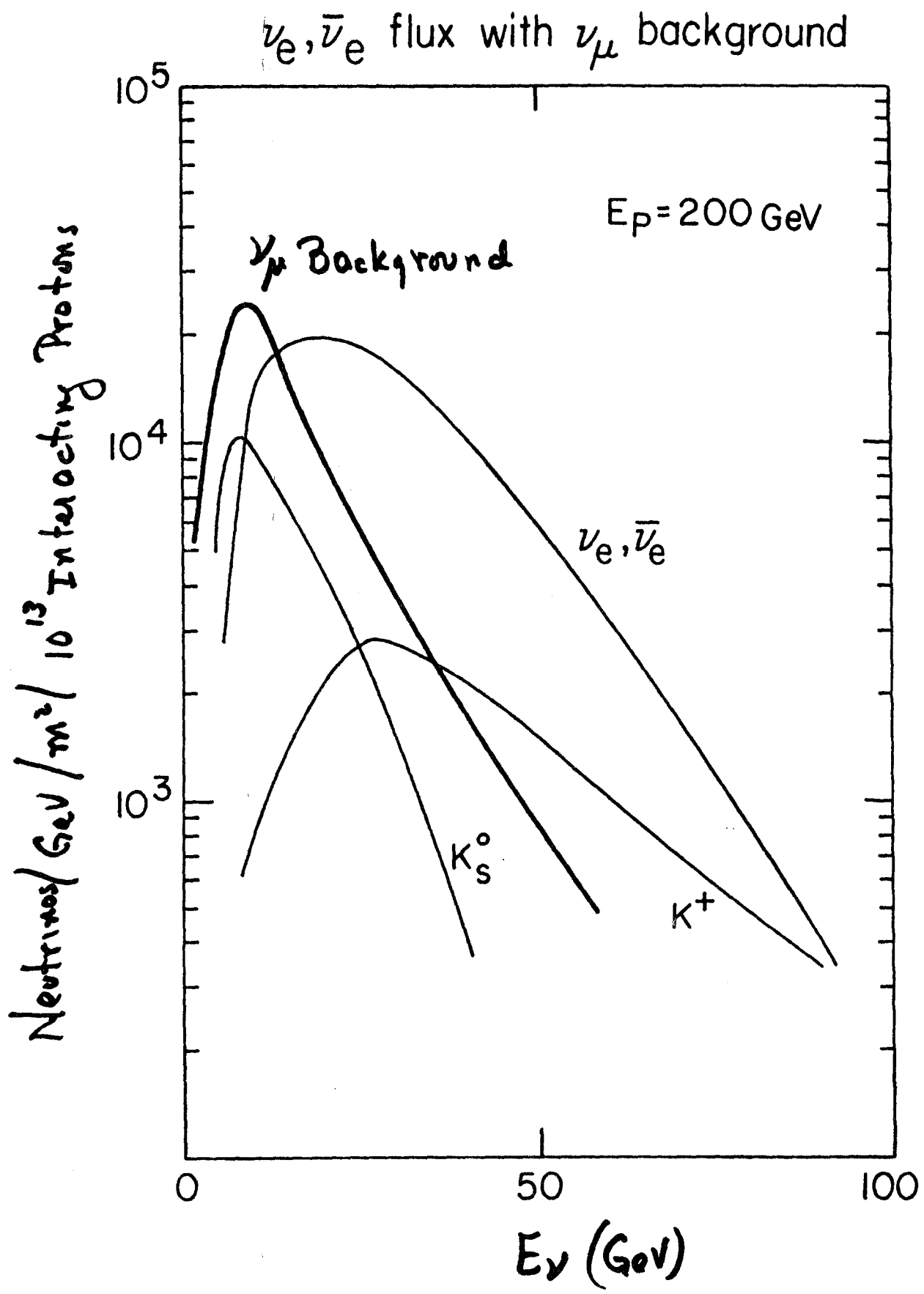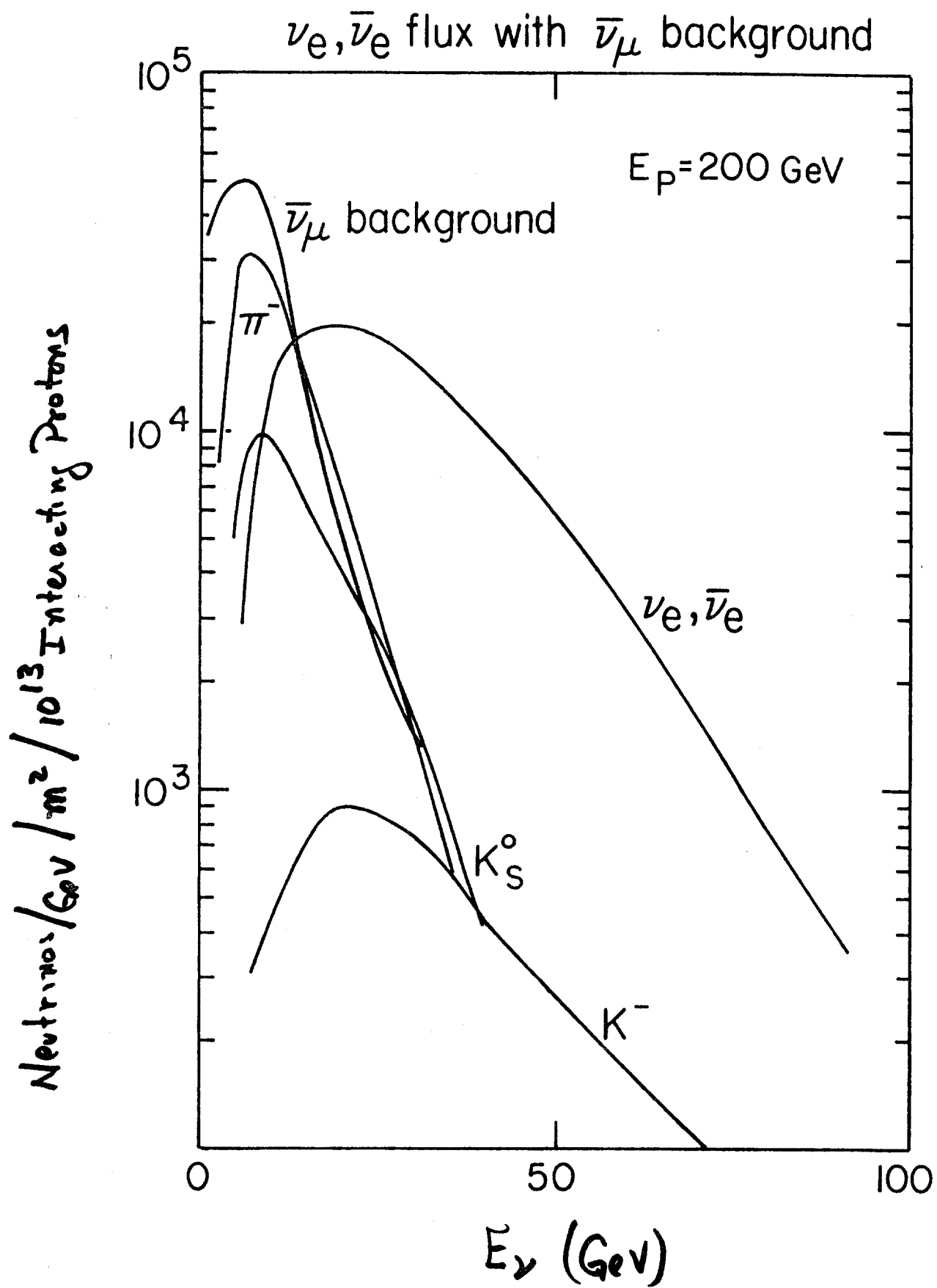E_ν (GeV)
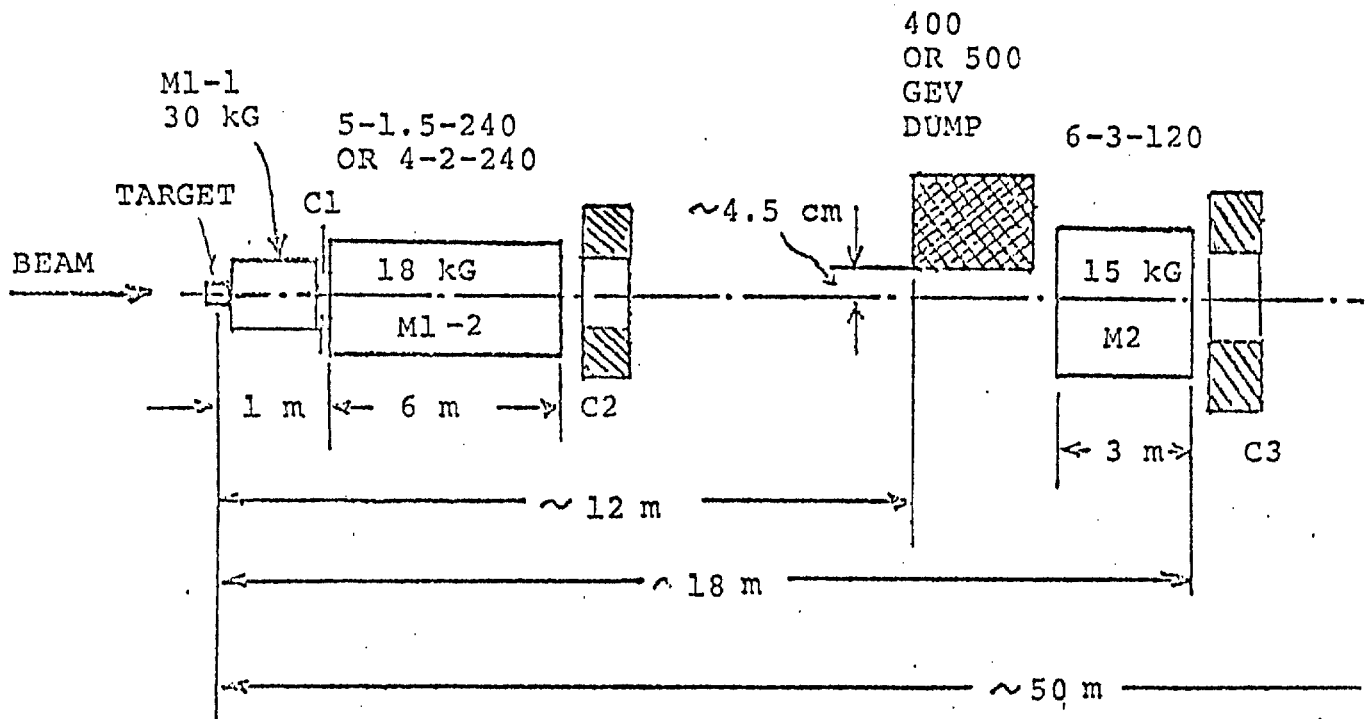
FIGURE 10

4. Event Rates and Detection Efficiency

We propose to fill the bubble chamber with a heavy neon mixture, about 15 tons of neon in the fiducial volume, we also assume 2×10^{13} protons per pulse. In a 500,000 picture exposure we expect 2000 ν_e interactions and 1000 $\bar{\nu}_e$ interactions for 400 GeV operation using the spectra shown in Figure 8. We expect comparable numbers for 200 GeV operation.

However, the operation of the machine in a dedicated experiment at 200 GeV primary beam energy could have several important advantages.

i)   About $3\text{-}3.5 \times 10^{13}$ proton could <u>reliably</u> be delivered on target with a ~ 3 second cycle time with no flat-top.

ii) The accelerator power requirements are greatly reduced.

iii) Such a run of about six weeks would result in $\sim 3 \times 10^{19}$ protons on target or more than 5000 ν_e events. The short duration of the run will minimize the bubble chamber operational costs and enable a prompt analysis of the data.

The threshold cross section behavior of $\tau^{\pm}$ production will suppress the low energy ν_τ, $\bar{\nu}_\tau$ rates as shown in Figure 5.

The expected detection efficiency for $\tau^{\pm}$ identification depends on the backgrounds in the bubble chamber. In priniciple all the decay modes of the $\tau^{\pm}$ could be detected either through

$$\nu_\tau + N \rightarrow \tau^- + x$$
$$\hookrightarrow \text{charged lepton + missing } P\perp$$

or

$$\rightarrow \tau^- + x$$
$$\hookrightarrow \text{hadron jet + missing } P\perp \Big\} \quad \text{double jet events}$$

The latter process is separated from the ordinary neutral current processes

$$\nu_{e,\mu} + N \rightarrow \nu_{e,\mu} + x$$

through the two jet signature.

For solution C we expect $\lesssim 250$ detected τ events and for solution A $\lesssim (5\text{-}10)$ events. We believe that the background rates are sufficiently low to be able to clearly separate the signal from the background in either case.

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POSSIBLE INDICATIONS OF NEUTRINO OSCILLATIONS

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ABSTRACT

We analyze neutrino oscillations of the ν_e, ν_μ, ν_τ system. Presently available reactor antineutrino data contain indications of oscillations, that have hitherto escaped attention, corresponding to an eigenmass squared difference of $\delta m^2 = 1$ eV^2. Two other classes of oscillation solutions are contrasted and further experimental tests are indicated. All the δm^2 must be greater than 10^{-3} eV^2 to explain solar and deep mine observations.

The interesting possibility of neutrino oscillations has long been recognized[1] but no clear signal has yet been established.[2] In this Letter we observe, however, that the reactor antineutrino data of Reines et al.[3,4] are consistent with an oscillation effect of shorter wavelength than hitherto considered. Solar neutrino observations and deep mine neutrino data reinforce the indication that neutrino oscillations occur, and constrain their parameters.

Neutrino oscillations depend on differences in mass m_i between the neutrino mass eigenstates ν_i. The latter are related to the weak charged current eigenstates ν_α (distinguished by Greek suffices) through a unitary transformation $|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle$. Starting with an initial neutrino ν_α of energy E, the probability for finding a neutrino ν_β after a path length L can be compactly written (for $E^2 \gg m_i^2$):

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} + \sum_{i<j} 2|U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j}|\,[(\cos(\Delta_{ij}-\phi_{\alpha\beta ij})-\cos\phi_{\alpha\beta ij}] \quad (1)$$

where $\phi_{\alpha\beta ij} = \arg(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})$ and $\Delta_{ij} = \tfrac{1}{2}(m_i^2-m_j^2)L/E$. For a diagonal transition or an off-diagonal transition with CP conservation (U real), we obtain the simple formula

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - \sum_{i<j} 4U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\,\sin^2(\tfrac{1}{2}\Delta_{ij}) \ . \quad (2)$$

With L/E in m/MeV and m_i in eV units, the oscillation argument in radians is

$$\tfrac{1}{2}\Delta_{ij} = 1.27\ \delta m_{ij}^2\ L/E \quad (3)$$

where $\delta m_{ij}^2 \equiv m_i^2 - m_j^2$. For antineutrinos replace U by U^* above.

The oscillations are periodic in L/E. Oscillations arising from a given δm_{ij}^2 can be most readily mapped out at L/E values of order $1/\delta m_{ij}^2$. The

experimentally accessible ranges of L/E in m/MeV are $\sim 10^{10}$ (solar), ~ 10-10^5 (deep mine), 1-7 (low energy accelerators), 1-20 (reactors), 0.3-3. (meson factories), and 0.01-0.05 (high energy accelerators). After many cycles, detectors cannot measure L or E precisely enough to resolve individual oscilla- tions and are sensitive only to average values. In the limit L/E $\gg$ $(m_i^2 - m_j^2)^{-1}$ for all i $\neq$ j, the average asymptotic values are given by

$$\langle P(\nu_\alpha \rightarrow \nu_\beta) \rangle = \sum_i |U_{\alpha i} U_{\beta i}^*|^2 . \tag{4}$$

Since only ν_e, ν_μ, and ν_τ neutrino types are known, we specialize to a three neutrino world. The matrix U can then be parameterized in the form introduced by Kobayashi and Maskawa,[5] in terms of angles $\theta_1, \theta_2, \theta_3$ with ranges $(0, \pi/2)$ and phase δ with range $(-\pi, \pi)$. In our present analysis we neglect CP violation (thus δ = 0 or $\pm \pi$). To limit the regions of the θ_i, δm_{ij}^2 para- meter space, we consider first the constraints placed by solar, deep mine and accelerator data.

Solar neutrino observations and deep mine experiments: The solar neutrino data[6] suggest that $\langle P(\nu_e \rightarrow \nu_e) \rangle \simeq$ 0.3-0.5 at L/E $\sim 10^{10}$ m/MeV. For three neu- trinos, Eq. (4) gives

$$\langle P(\nu_e \rightarrow \nu_e) \rangle = c_1^4 + s_1^4 c_3^4 + s_1^4 s_3^4 \tag{5}$$

where $c_i = \cos\theta_i$ and $s_i = \sin\theta_i$. The minimum value of Eq. (5) is 1/3 and this requires $c_1 = 1/\sqrt{3}$, $c_3 = 1/\sqrt{2}$. For $\langle P(\nu_e \rightarrow \nu_e) \rangle$ to be near its minimum, all mass differences must satisfy $\delta m^2 \gg 10^{-10}$ eV^2. At this minimum all transition averages are specified, independent of θ_2; in particular $\langle P(\nu_\mu \rightarrow \nu_\mu) \rangle$ = 1/2. In fact, there are indications from deep mine experi- ments[7-9] that $\langle P(\nu_\mu \rightarrow \nu_\mu) \rangle \sim$ 1/2 (see footnote f in Table 1). Since the ν_μ

neutrinos detected in deep mines have traversed terrestrial distances, this measurement suggests that all $\delta m^2 \gtrsim 10^{-3}$ eV^2. Based on these considerations we may suppose that the true solution is not far from the above θ_1, θ_3 values. If we only require $<P(\nu_e \to \nu_e)> <0.5$, then θ_1 and θ_3 are constrained to a region approximated by the triangle $\theta_1 > 35°$, $\theta_3 > \theta_1 - 45°$, and $\theta_3 < 135° - \theta_1$.

$\underline{\nu_\mu \to \nu_e, \nu_\tau \text{ oscillations}}$: Stringent experimental limits exist on these transitions[10-13] at L/E in the range 0.01 to 0.3 m/MeV (see Table 1). For $\delta m^2 << 1$ eV^2, these oscillations do not appear until L/E $>> 1$ m/MeV. With a single $\delta m^2 \gtrsim 1$ eV^2, these oscillations can be suppressed by choice of θ_2 (if θ_1, θ_3 are taken as above).

$\underline{\text{Reactor } \overline{\nu}_e\text{-oscillations}}$: The $\overline{\nu}_e$ flux at distances L = 6 m and 11.2 m from a reactor core center was measured by Reines et al.,[3,4] using the known cross section for the inverse beta-decay reaction $\overline{\nu}_e p \to e^+ n$. The reactor $\overline{\nu}_e$ flux at the core has been calculated using semi-empirical methods.[14-17] The ratio of measured flux at L to the calculated flux measures $P(\overline{\nu}_e \to \overline{\nu}_e)$. Neutrino oscillation interpretations of the data thereby depend on the calculated spectrum about which there is some uncertainty.

Figure 1 shows a comparison of the measured $\overline{\nu}_e$ flux at L = 6 m and L = 11.2 m with calculated spectra. We note that the Avignone-1978 calculated flux[16] accommodates best the L = 6 m measurements for $E_{\overline{\nu}_e} > 6$ MeV. The data for $P(\overline{\nu}_e \to \overline{\nu}_e)$ obtained with the Avignone-1978[16] and Davis et al.[17] calculated spectra are shown in Fig. 2. The horizontal error bars in Fig. 2 take into account the finite size of the reactor core source. We observe that $P(\overline{\nu}_e \to \overline{\nu}_e)$ seems to follow an oscillation pattern with one node in the range of L/E covered by the measurements. The possibility of such a solution

in which a short wavelength oscillation occurs was not considered by Reines et al.[3] in their analysis of the 11.2 m data based on a similar calculated spectrum.[15]

The oscillation in Fig. 2 is well-described by the formula $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - 0.44 \sin^2(1.27 \, L/E)$. This corresponds to a mass difference $\delta m^2 = 1 \, \text{eV}^2$, which we can arbitrarily identify as δm_{13}^2. A non-zero δm_{12}^2 with $\delta m_{12}^2 \ll \delta m_{13}^2$, is required to bring $\langle P(\nu_e \rightarrow \nu_e) \rangle$ down asymptotically to the solar neutrino result. The value of δm_{12}^2 is not tightly constrained, other than the indication from deep mine measurements of $\langle P(\nu_\mu \rightarrow \nu_\mu) \rangle$ that $\delta m_{12}^2 \gtrsim 10^{-3} \, \text{eV}^2$. A solution which accommodates all known constraints is

	δm_{13}^2	δm_{12}^2	θ_1	θ_2	θ_3	δ
SOLUTION A:	$1.0 \, \text{eV}^2$	$0.05 \, \text{eV}^2$	$45°$	$25°$	$30°$	$0°$.

$$(5)$$

The predictions for subasymptotic transition probabilities are shown in Fig. 3.

A more conservative interpretation of the reactor $\bar{\nu}_e$ data could be that $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ falls to around 0.7-0.8 in the range of L/E considered, but that oscillatory behavior is not established. If so, two other classes of solution are possible: Class B, where $\bar{\nu}_e \rightarrow \bar{\nu}_e$ is suppressed by the onset of a long wavelength oscillation, that may have its first node well beyond L/E = 1 m/MeV; Class C, where $\bar{\nu}_e \rightarrow \bar{\nu}_e$ is suppressed by a short wavelength oscillation, that may have many nodes below L/E = 1 m/MeV. Illustrative solutions of these classes are as follows (we emphasize that their parameters are less constrained than in Class A).

	δm^2_{13}	δm^2_{12}	θ_1	θ_2	θ_3	δ	
SOLUTION B:	0.15 eV^2	0.05 eV^2	55°	0°	45°	0°	(6)
SOLUTION C:	10 eV^2	0.05 eV^2	45°	25°	30°	0° .	

We note that equivalent solutions to Eqs. (5) and (6) are obtained with $\delta m^2_{13} \leftrightarrow \delta m^2_{12}$, $\delta = \pi$, and $\theta_3 \rightarrow \frac{\pi}{2} - \theta_3$ with θ_1, θ_2 unchanged. Table 1 presents a capsule summary of the present experimental limits on oscillations and summarizes predictions of solutions A, B and C for existing and planned experiments. For the L/E range of the CERN beam dump experiment,[19] a $\delta m^2 \gtrsim 10$ eV^2 is required to yield an e/μ ratio that is significantly less than unity.[2b] In solution C, which has a δm^2 in that range, the mixing angles are nearly the same as those contained in ref. 2b. Solution A has the same mixing matrix as solution C, but the smaller value of δm^2_{13} leads to visible oscillations in reactor experiments rather than in high energy beam dump experiments.

New reactor experiments: Reactor measurements[3] in the L/E range 5-20 m/MeV could provide information on δm^2_{12}. For $\delta m^2_{12} \ll 0.05$ eV^2 solutions A and C predict no appreciable deviation from a $1/r^2$ fall-off of the average flux at L/E > 5 m/MeV.

New meson factory experiments: Since the decays of stopped μ$^+$ mesons provide well-known ν_e and $\bar{\nu}_\mu$ spectra, meson factory experiments at L/E ∿ 1-3 m/MeV[24] could confirm the existence of $\nu_e \rightarrow \nu_e$ oscillations and place further constraints on $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.

Summary: Reactor $\bar{\nu}_e$ data provide indications of neutrino oscillations with mass scale $\delta m^2 = 1$ eV^2. Solar and deep mine results suggest that the other mass scale is in the range $\delta m^2 \gtrsim 10^{-3}$ eV^2.

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TABLE REFERENCES

a   San Onofre reactor experiment by Reines et al.[3] in progress, with
    L = 25-100 m.

b   Possible LAMPF experiment with E_{ν_e}, $E_{\bar{\nu}_\mu}$ = 30-50 MeV and L = 30-100 m.

c   Brookhaven experiment[18] in data analysis stage.

d $\nu_e \rightarrow \nu_\tau$ oscillations can lead to a e/μ ratio different from unity in beam
    dump experiments (see e.g., ref. 2b and data of ref. 19).

e   The excellent agreement of observed and calculated $\nu_e / \bar{\nu}_e$ flux at CERN
    and Fermilab indicates that most of the ν_e does not oscillate into ν_τ.

f   Deep mine experiments[7,8] have detected about 130 neutrino events
    (E $\sim 10^4$-10^6 MeV, L $\sim 10^6$-10^7 m). An unaccountably large number of
    multitrack events were observed in the Kolar gold field experiment;[7]
    assuming that these are not attributed to ν_μ, the event rate is about
    half the expected rate. In the Johannesburg mine experiment[8] a ratio
    1.6 ± 0.4 of expected to observed ν_μ events was found. The analysis in
    ref. 9 of these experiments is consistent with $<P(\nu_\mu \rightarrow \nu_\mu)> \sim 0.5$. A new
    deep mine experiment is operating at Baksan, USSR which is sensitive to
    ν_μ flux through the earth.[20]

g   Deep mine experiments in construction[21] will detect neutrinos of ener-
    gies E $\sim 10^2$-10^3 MeV using very large water detectors placed in deep
    mines. At these energies the composition[22] of the ν-flux from π, K,
    and μ decays of the secondary cosmic ray component in the atmosphere
    is roughly $(2\nu_\mu + \nu_e)/3$. Upward events in the detector will have
    L $\simeq 10^6$-10^7 m and downward events will have L $\simeq 10^4$ m. The charged-
    current scattering of ν_e on electrons significantly modifies vacuum
    oscillation predictions only for deep mine events which have
    $E(MeV) \gtrsim 10^6$ $\delta m^2 (eV^2)$; see ref. 23.

TABLE 1

Experimental Limits on Neutrino Oscillations and Neutrino Flux Predictions

Observable	Source Refs.	$\frac{L}{E} \frac{m}{MeV}$	Present Limit	Solution A	Solution B	Solution C
$\langle P(\nu_e \to \nu_e)\rangle$	S 6	10^{10}	$\gtrsim \frac{1}{4}, \lesssim \frac{1}{2}$	0.41	0.33	0.41
$P(\bar\nu_e \to \bar\nu_e)$	R 3,4	1-3	> 0.5	0.6-1.0	0.8-1.0	0.8 mean
	R a	5-20		0.1-0.9	0.05-0.5	0.1-0.9
$P(\nu_e \to \nu_e)$	A	0.04	> 0.85 e	1.0	1.0	0.9
	M 12	0.3	1.1 ± 0.4	0.95	1.0	0.8 mean
	M b	1-3		0.6-1.0	0.8-1.0	0.8 mean
$P(\bar\nu_\mu \to \bar\nu_e)$	M 12	0.3	< 0.04	10^{-4}	10^{-3}	10^{-3}
	M b	3		0.03	0.11	0.03
$P(\nu_\mu \to \nu_e)/P(\nu_\mu \to \nu_\mu)$	A 10,11	0.04	$< 10^{-3}$	10^{-6}	10^{-5}	10^{-4}
$P(\nu_\mu \to \nu_\tau)/P(\nu_\mu \to \nu_\mu)$	A 18 c	1-7		0-0.2	0-0.8	0-0.2
$P(\nu_e \to \nu_\tau)$	A d	0.04	< 0.2 e	10^{-3}	10^{-5}	0.1
$P(\nu_\mu \to \nu_\tau)/P(\nu_\mu \to \nu_\mu)$	A 13	0.04	$< 2.5\times10^{-2}$	10^{-5}	10^{-5}	10^{-3}
$\langle P(\nu_\mu \to \nu_\mu)\rangle$	D f	10^2-10^3	≈ 0.5	0.51	0.51	0.51
$\langle P(\nu_c \to \nu_\mu)\rangle$	D g	10^3-10^5		0.48	0.44	0.48
$\langle P(\nu_c \to \nu_e)\rangle$	D g	10^3-10^5		0.42	0.33	0.42
$P(\nu_c \to \nu_\mu)$	D g	$10-10^2$		0.3-0.7	0.3-0.7	0.3-0.7
$P(\nu_c \to \nu_e)$	D g	$10-10^2$		0.2-0.6	0.2-0.6	0.2-0.6

Notation: S(solar), R(reactor), M(meson factory), A(accelerator), D(deep mine); $\nu_c \approx (2\nu_\mu + \nu_e)/3$.

FIGURE CAPTIONS

Fig. 1   The $\overline{\nu}_e$ reactor flux measurements of Reines et al. at L = 11.2 m

(ref. 3) and L = 6 m (ref. 4) compared with the calculated

spectra of refs. 3, 4, 14-17.

Fig. 2   Transition probability $P(\overline{\nu}_e \to \overline{\nu}_e)$ versus L/E deduced from the

ratio of the observed to the calculated $\overline{\nu}_e$ reactor flux from

refs. 16-17. The curve represents neutrino oscillations with

an eigenmass difference squared of $\delta m^2 = 1$ eV^2 (SOLUTION A of

Eq. (5)).

Fig. 3   *Subasymptotic neutrino oscillations for all channels based on*

SOLUTION A in Eq. (5). Arrows on the right-hand side denote
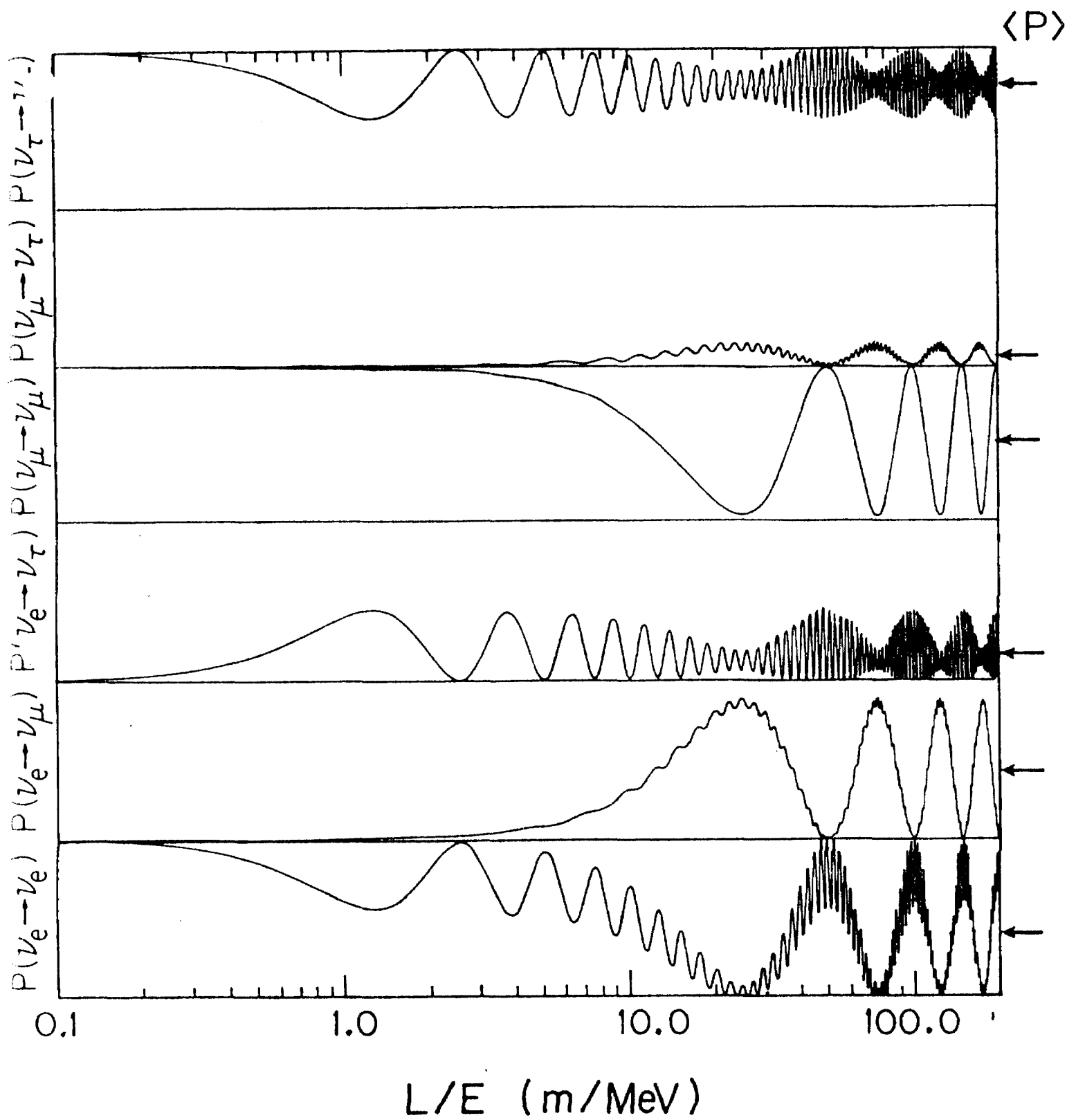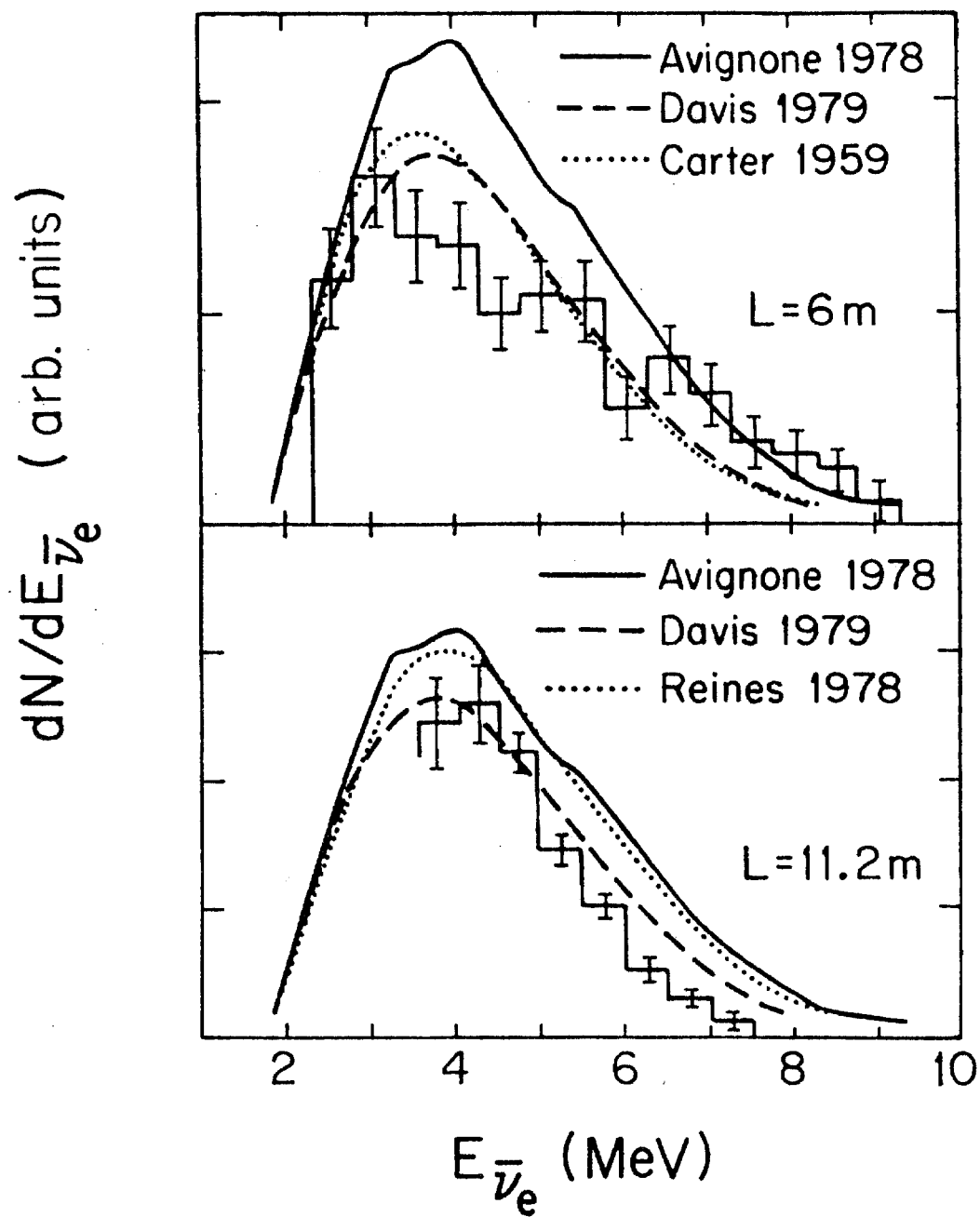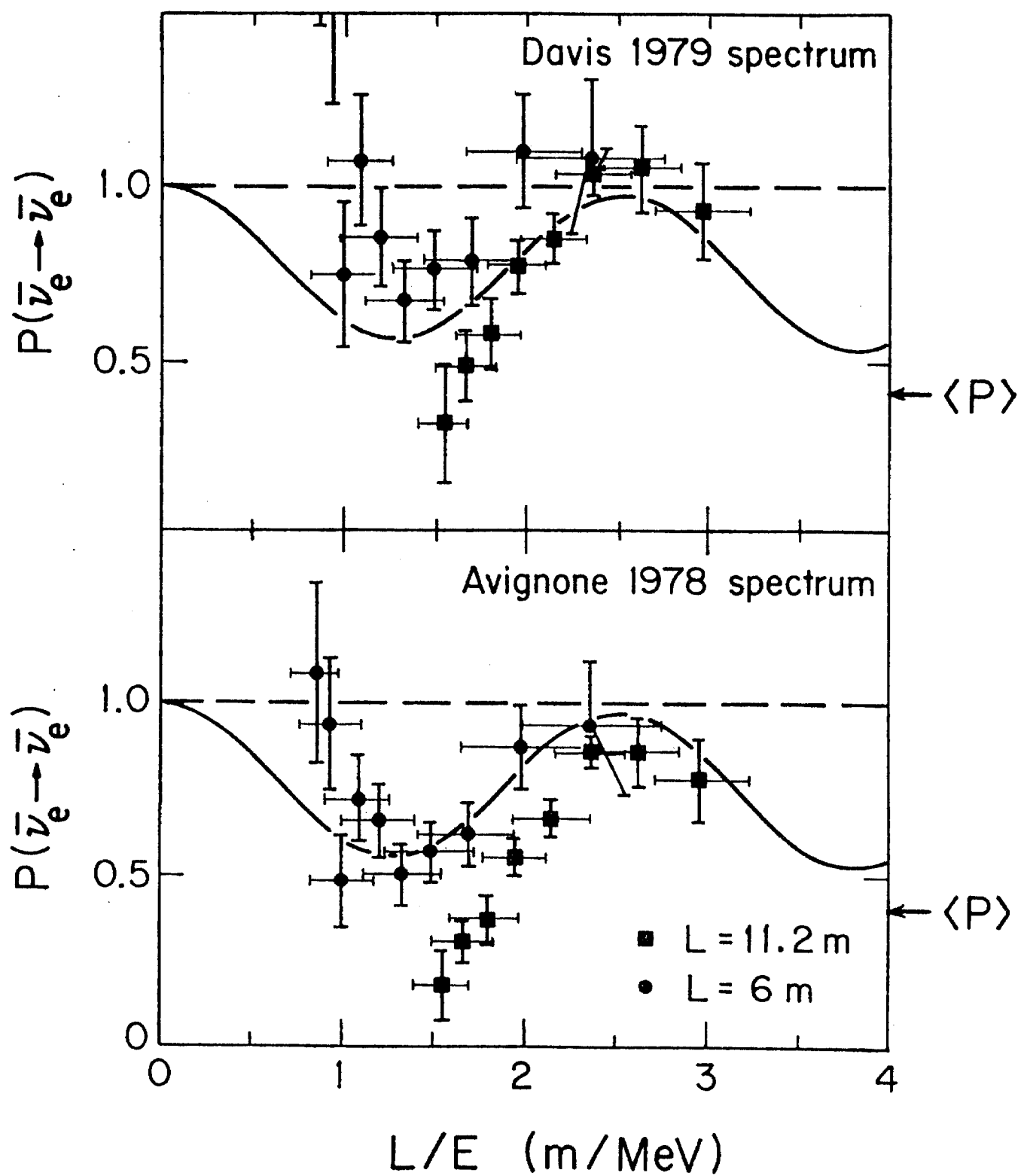
asymptotic mean values.

Fig. 3

Fig. 1

Fig. 2

MASS AND MIXING SCALES OF NEUTRINO OSCILLATIONS

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ABSTRACT

The extraction of neutrino oscillation parameters from the ratio of rates $(\bar{\nu}_e d \to e^+ nn)/(\bar{\nu}d \to \nu pn)$ is considered in the context of oscillations proposed to account for previous reactor data. The possibility that only ν_e, ν_μ oscillations occur is shown to be barely compatible with present limits on $\nu_\mu \to \nu_e$ transitions. Predictions for $\nu_e, \nu_\mu \to \nu_\tau$ oscillations are made for future accelerator experiments.

Neutrino oscillations[1-3] are of great interest because of the light they may shed on neutrino mass scales and mixing angles. The solar neutrino puzzle[2-4] may indicate oscillations and a e/µ discrepancy in the CERN beam dump experiment has also been speculated upon[5]. Recently we presented[6] a reexamination of all neutrino flux data, including the old reactor $\bar{\nu}_e$ measurements by Reines and collaborators.[7] We drew the conclusion that the oscillation probability $P(\bar{\nu}_e \to \bar{\nu}_e)$ falls to 0.5 or lower in the neighborhood of $L/E = 1.5$ m/MeV, where L is the distance from the source and E is the energy. Interpretating this as an oscillation effect, we showed that neutrino-mixing with a leading mass squared difference of the order of 1 eV^2 matched the reactor data in some detail (solution A of ref. 6). Qualitatively different classes of solutions were considered for comparison, with a δm^2 considerably smaller (solution B) or considerably larger (solution C) than 1 eV^2.

Further evidence for neutrino oscillations from reactor experiments comes from the simultaneous consideration of charged current (CC) and neutral current (NC) deuteron disintegration reactions[8]

$$\bar{\nu}_e d \to e^+ nn \qquad\qquad \bar{\nu}d \to \bar{\nu}pn \ . \qquad\qquad (1)$$

The neutral current process is immune to oscillations, being the same for all types of antineutrinos in the standard theory and effectively monitors the initial $\bar{\nu}$ flux. The ratio of CC/NC rates is rather insensitive to theoretical uncertainties in the calculated $\bar{\nu}_e$ spectrum from the reactor (the principle uncertainty hitherto) and can be used to extract neutrino oscillation parameters. In the present letter we calculate the NC/CC ratios predicted for this experiment by the solutions of ref. 6 and discuss the constraint on δm^2 and mixing angles. The possibility of having oscillations only in the ν_e, ν_μ system is

shown to be barely compatible with reactor data and present experimental limits on $\nu_\mu \to \nu_e$ transitions. For oscillations of three neutrinos, predictions of $\nu_e, \nu_\mu \to \nu_\tau$ oscillations are made for future accelerator experiments.

The spectrum averaged cross sections for deuteron disintegration have the form

$$<\sigma> = \int_0^\infty dE_r \int_{E_{th}}^\infty dE_{\bar{\nu}} \; \rho(E_{\bar{\nu}}) \; f(E_{\bar{\nu}}) \; \frac{d\sigma}{dE_r} \qquad (2)$$

where $\rho(E_{\bar{\nu}})$ is the $\bar{\nu}_e$ flux at $L = 0$ and $f = P(\bar{\nu}_e \to \bar{\nu}_e)$ at $L/E_{\bar{\nu}}$ for the CC case and $f = \frac{1}{2}$ for the NC case. The variable E_r is the energy of relative motion of the final state nucleons; the recoil energy of the two-nucleon system can be neglected to a 1% approximation. The differential cross sections are[9]

$$\frac{d\sigma}{dE_r} = \frac{g_A^2 G_F^2 M_N^{3/2}}{2\pi^3} J_d^2(E_r)(E_{\bar{\nu}} - E_{th} + m)[(E_{\bar{\nu}} - E_{th} + m)^2 - m^2]^{\frac{1}{2}} E_r^{\frac{1}{2}} \qquad (3)$$

where M_N is the nucleon mass and $m = m_e$ for the CC and $m = 0$ for the NC. The threshold energies are

$$E_{th}^{CC} = 4.030 \text{ MeV} + E_r$$

$$(4)$$

$$E_{th}^{NC} = 2.225 \text{ MeV} + E_r$$

In Eq. (2) the quantity J_d is the overlap integral of deuteron wave functions describing the ^3S ground state and the ^1S continuum state, given by[9]

$$J_d = \frac{1.52 \times 10^{-3}(43.1 + 0.83 \, E_r)\text{MeV}^{-3/2}}{(E_r + 2.225)[E_r + (0.19 \, E_r + 0.27)^2]^{\frac{1}{2}}} \quad , \qquad (5)$$

with E_r in MeV units. With the exponential fall-off of $\rho(E_{\bar{\nu}})$ folded in, the dominant contribution to $<\sigma>$ comes from $E_r < 0.3$ MeV and $E_{\bar{\nu}} - E_{th} \simeq 0.5\text{-}3.5$ MeV. Thus oscillation effects can be measured in the range 4.6 - 7.6 MeV. We calculate the ratio

$$R_d \equiv \frac{<\sigma(\bar{\nu}_e d \rightarrow e^+ nn)>}{<\sigma(\bar{\nu}_e d \rightarrow \bar{\nu}_e pn)>} \tag{6}$$

with and without oscillations.

At $L \simeq 11.2$ m, $R_d(\text{osc})/R_d(\text{no osc})$ measures $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ over the range $L/E \simeq 1.5 - 2.4$, which is the region in which our analysis of the $\bar{\nu}_e p \rightarrow e^+ n$ data shows an oscillation effect.[6] Figure 1 shows the predictions, assuming that only one eigenmass-difference plays a significant role in the reactor range, for which

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\alpha \, \sin^2(1.27 \, \delta m^2 \, L/E) \tag{7}$$

with δm^2 in eV^2 units and L/E in m/MeV. The curves in Fig. 1 versus δm^2 represent mixing angles for which $\sin^2 2\alpha = 0.19$ (α = Cabibbo angle), 0.50, 0.80 and 1.0. These calculations are based on the Avignone-1978 reactor spectrum;[10] closely similar results are obtained with the Davis et al. spectrum.[11] Assuming ideal acceptance and allowing one standard deviation from the measured value of[8]

$$R_d(\text{osc})/R_d(\text{no osc}) = 0.43 \pm 0.17 \tag{8}$$

values of δm^2 are permitted in the ranges

$$0.3 < \delta m^2 < 1.1 \ eV^2 \qquad \delta m^2 > 1.7 \ eV^2 \tag{9}$$

for appropriate mixing angles α. The solution classes A and C of ref. 6

satisfy these criteria. For the preferred class A solutions, our analysis[6]

of the $\bar{\nu}_e p \rightarrow e^+ n$ data at L = 11.2 m gives the ranges

$$0.80 < \delta m^2 < 1.05 \text{ eV}^2$$

$$0.4 < \sin^2 2\alpha < 0.9 \ . \tag{10}$$

Results similar to Eqs. (9) and (10) were independently obtained in ref. 8.

Figure 2 shows predictions for $R_d(\text{osc})/R_d(\text{no osc})$ versus L for other reactor

experiments, based on solution A with $\delta m^2 = 0.8 \text{ eV}^2$ and the spectrum of

ref. 10.

Stringent limits[12,13] exist on $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at

$L/E \simeq 0.04$ m/MeV and on $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at $L/E \simeq 0.3$ m/MeV. If oscil-

lations occurred only between ν_e and ν_μ states and if a single δm^2 is dominant

below L/E = 3 m/MeV (as in solutions A and C of ref. 6), we can write

$$P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = P_o \sin^2(1.27 \ \delta m^2 \ L/E) \tag{11}$$

with the experimental bound

$$P_o < 0.3/(\delta m^2)^2 \ . \tag{12}$$

The corresponding bound on the mixing angle is

$$\sin^2 2\alpha < 0.3/(\delta m^2)^2 \ . \tag{13}$$

For $\delta m^2 \sim 1 \text{ eV}^2$, this is just on the borderline of admissibility by the

existing reactor data.

Applying similar considerations to oscillations of three neutrinos,

probability conservation leads to the predictions

$$P(\nu_e \rightarrow \nu_\tau) = P(\bar{\nu}_e \rightarrow \bar{\nu}_\tau) = [\sin^2 2\alpha - P_o] \sin^2 (1.27 \ \delta m^2 \ L/E) \ .$$

$$\text{(14)}$$

$$P(\nu_\mu \rightarrow \nu_\tau) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau) = [P_o/(4 \ \sin^4 \alpha)] \ P(\nu_e \rightarrow \nu_\tau) \ .$$

Thus three neutrino oscillations can be tested by detecting ν_τ, $\bar{\nu}_\tau$ produced in a ν_e, ν_μ beam that is free of ν_τ and $\bar{\nu}_\tau$. The ν_τ, $\bar{\nu}_\tau$ are detected through the interactions

$$\nu_\tau n \rightarrow \tau^- X^+$$

$$\text{(15)}$$

$$\bar{\nu}_\tau p \rightarrow \tau^+ X^o \ .$$

Figure 3 shows predictions for $P(\nu_e \rightarrow \nu_\tau)$ for the L/E range of high energy accelerators (the two curves for solution A corresponding to P_o between 0 and 0.3, with $\delta m^2 = 1 \ eV^2$). $P(\nu_\mu \rightarrow \nu_\tau)$ depends critically on P_o and can be larger than $P(\nu_e \rightarrow \nu_\tau)$.

Solution C has been of primary interest in connection with the e/μ ratio of beam dump experiments.[5] By increasing the scale of the δm^2, it is possible to construct an alternate version of solution C (solution C') which can explain both reactor and beam results by having a short wavelength oscillation (such as $\delta m_{13}^2 \simeq 50 \ eV^2$) superimposed on a long wavelength oscillation ($\delta m_{12}^2 \simeq 1 \ eV^2$). Representative six-quark mixing angles for such a solution are

$$\theta_1 = 30° \qquad \theta_2 = 50° \qquad \theta_3 = 55° \qquad \delta = 0° \ . \tag{16}$$

Solution C' gives $R_d(osc)/R_d(no \ osc) = 0.59$ at $L = 11.2$ m; the minimum value of $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ in the reactor range is 0.47 when averaged over the short wavelength oscillation. Predictions of $P(\nu_e \rightarrow \nu_\tau)$ for this solution are also given in Fig. 3.

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FIGURE CAPTIONS

Figure 1   Neutrino oscillation results for the quantity $R_d(osc)/R_d(no\ osc)$
with R_d as defined in Eq. (6).

Figure 2   Predictions for $R_d(osc)/R_d(no\ osc)$ versus distance L from the
reactor core, based on solution A with $\delta m^2 = 0.8\ eV^2$.

Figure 3   Predicted $\nu_e \to \nu_\tau$ transition probability for the L/E range of
high energy accelerators.   The δm^2 values are 1 eV^2 for
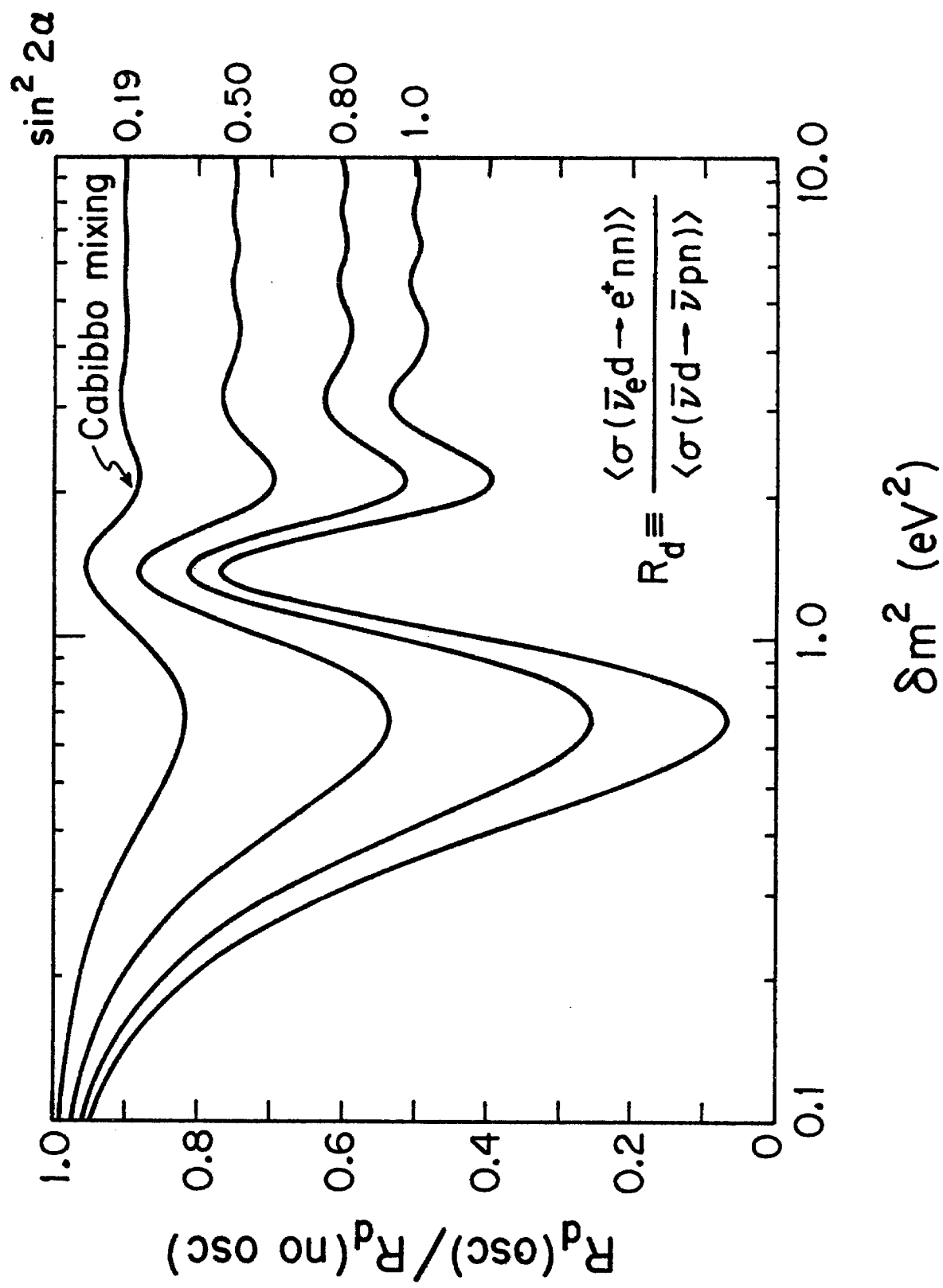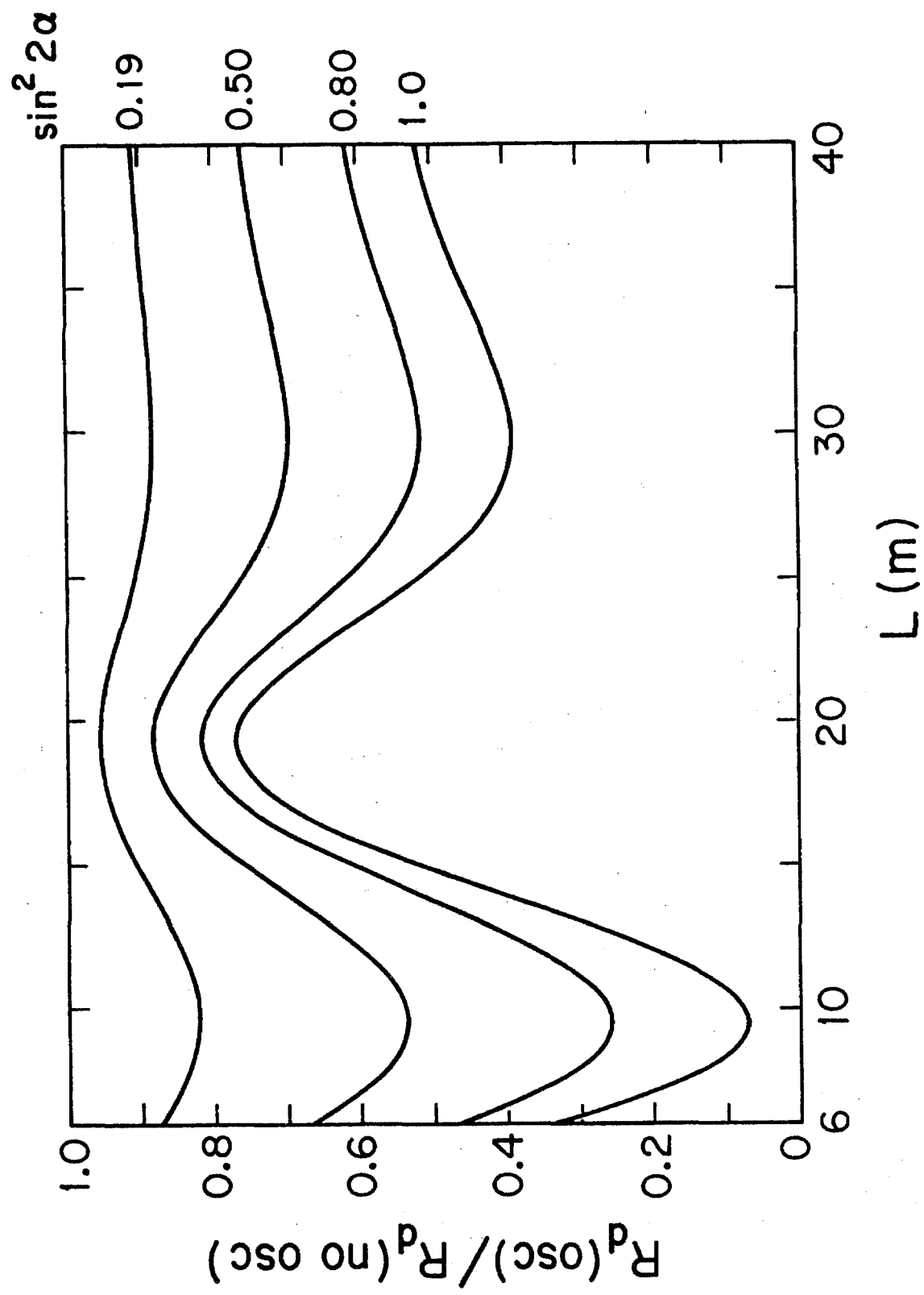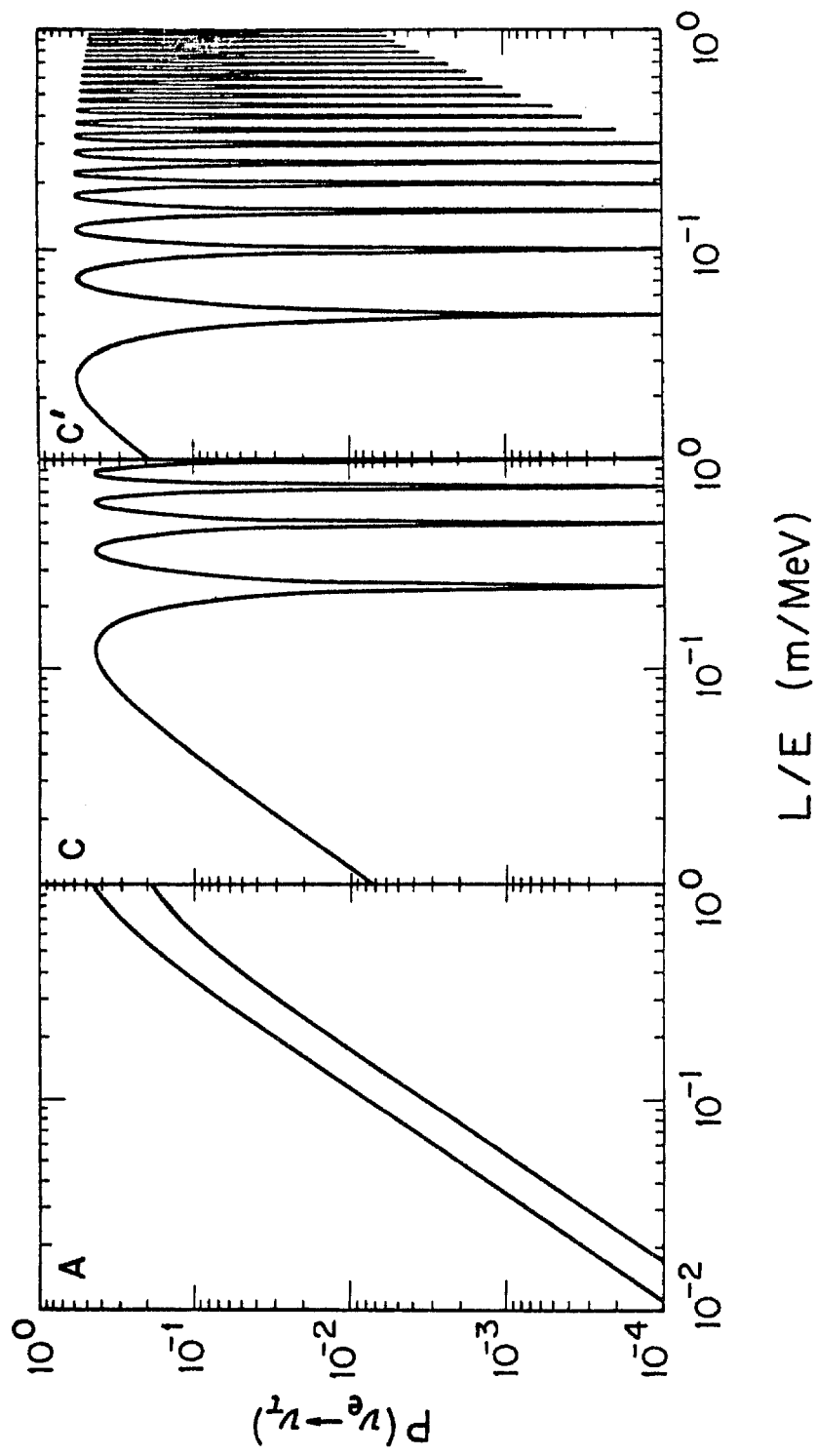solution A, 10 eV^2 for C, 50 eV^2 and 1 eV^2 for C'.

$$\sin^2 2\alpha$$

0.19

0.50

0.80

1.0

Cabibbo mixing

$$R_d \equiv \frac{\langle \sigma(\bar{\nu}_e d \rightarrow e^+ nn) \rangle}{\langle \sigma(\bar{\nu} d \rightarrow \bar{\nu} pn) \rangle}$$

$R_d(\text{osc})/R_d(\text{no osc})$

δm^2 (eV^2)

Figure 1

Figure 2

$P(\nu_e \rightarrow \nu_\tau)$

L/E (m/MeV)

Figure 3